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The instrument geometrical parameters calculation theory for the pressure processing of the round-rolled surface

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Abstract. The problem of round-rolled surface products improving quality by reducing roughness and waviness is solved. Traditionally, grinding is used to improve the surface quality, but at the same time new defects appear in the form of cracks, tinge colours and the abrasive particles infiltration into the surface layer. Surface pressure processing instead of grinding is not associated with such defects, therefore, it is proposed to use a transverse rolling. Rolling rational profile for transverse rolling of round-rolled surface was theoretically determined. Analytical dependences were obtained for rolls in cage with support rings calibration calculations. Such calibration use ensures uniform deterioration of rolls and rings bearing surfaces, as well as the rolls balance with their one-sided load during rolling. A parametric analysis of the deformation conditions effect on the rolls geometry was performed. The conditions when rolls profile can be limited to a circle or a straight line were considered. The obtained results were used in rolls profiling for drawing the rolling surface in laboratory and industrial conditions.

1. Introduction
The domestic metal products surface quality indicators significantly affect its competitiveness in the global metal market [1]. The international market has high demands on the macro- and microgeometry of the round-rolled surface. Meeting these requirements ensures the finished product presentation and the reliability of the ultrasound metal control (USC) [2, 3].

2. Problems with the rolled surface quality
Rolled surface treatment for removing the defective layer is the final operation of the production [4]. The main indicators of surface quality after processing are roughness and waviness [5]. To improve the surface quality, rolls of various diameters are ground on centerless lathes [6]. The roughness in this case is *Ra* 2,5, and the wave height under the cutter – 0,03 mm, which does not always meet the requirements for rolling with a special surface finish [7]. Further reduction of roughness and wave height requires the use of additional finishing operations. Traditionally, centerless grinding is used for this purpose. However, during grinding, surface defects such as scratches, cracks, burns, discoloration colours and the infiltration of abrasive particles into the surface layer also occur [8]. Thus, it becomes necessary to apply more efficient methods for finishing the surface of metalrolling.

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Another way to improve the quality is plastic deformation of the surface layer by transverse rolling [9–15]. While transverse rolling on centerless lathes, the rolls perform a planetary movement around the cage that moves without rotation along its axis [16]. There are significant loads on the cage structure while plastic deformation. Increasing the load capacity of the structure is achieved by using a cage with support rings for rolls [17, 18].

The rolling scheme is shown in figure 1. From this figure its follows that rolling deformation zone is located on one side of the roll. Therefore, the load acting on the bearing surface on the right side of the roll is greater than on the left. This leads to uneven deterioration of the rolls and supporting rings opposite surfaces.

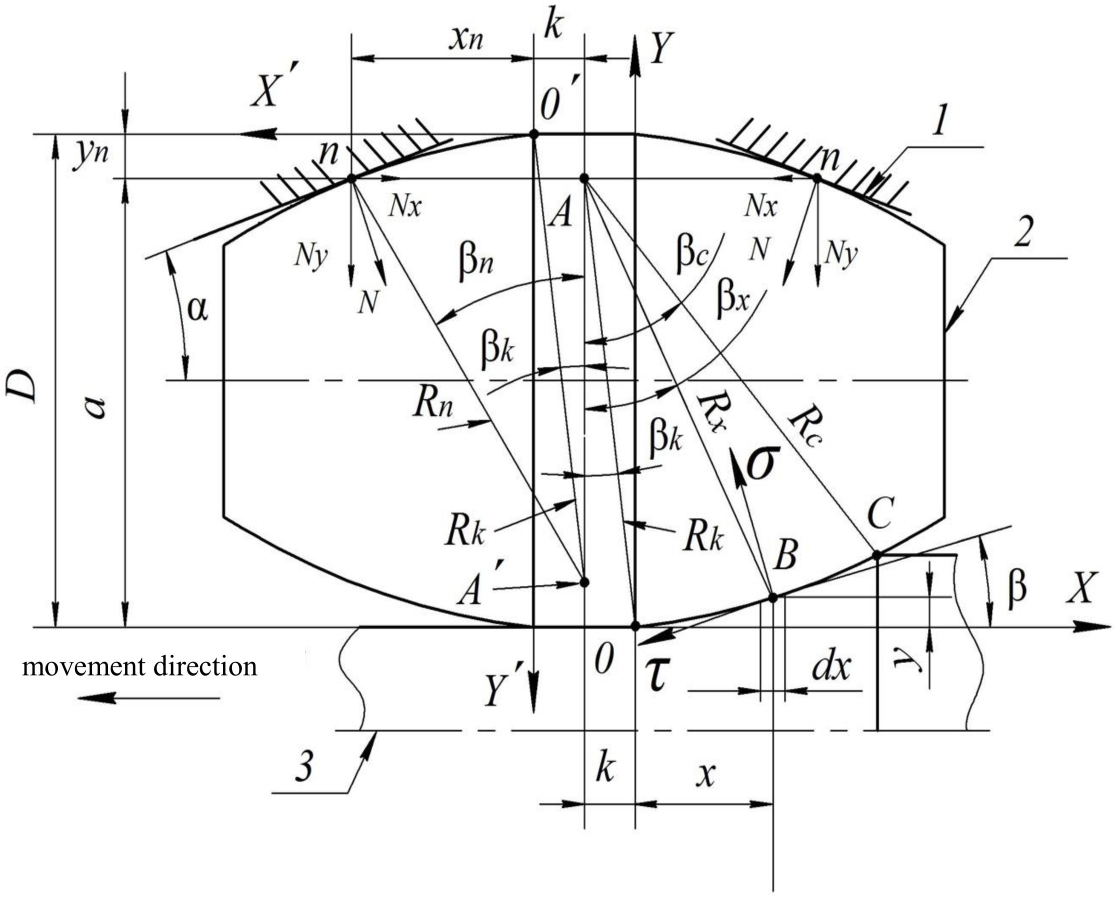

Figure 1. Round-roll rolling scheme.

1 - supporting ring; 2 - roll; 3 – rolling

The purpose of this work is to determine the working surface profile of the roll, at which the loads acting on the bearing surfaces will be the same, and that will ensure uniform deterioration of the rolls and supporting rings bearing surfaces, as well as the rolls balance the under one-sided load during rolling.

3. Rolls profile calculation theory

Let's write the roll balance equation relative to a point A provided that the support reactions N at the points n are equal. The sum of the support reactions moments relative to the point A equals zero (figure 1). Select in the axial section of the roll near the point B section length dx. From the side of the metal to the roll acting normal pressure force σ and friction force τ, associated with σ Coulomb's Law:

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$\tau = \sigma f$; where f – friction coefficient. The elementary moment of these forces relative to the point A at roll equilibrium is zero, i.e.:

$$dm_A = (\tau_y - \sigma_y)(x+k)dx + (\sigma_x + \tau_x)(a-y)dx = 0. \tag{1}$$

Where $\sigma_x, \sigma_y, \tau_x, \tau_y$ – projection of forces σ and τ on axis x and y; k – half length of the calibration roll; a – distance from the roll barrel to the point; x and y – point B coordinates in the coordinate system $X0Y$ with the beginning at the point of interface of the roll profile with the calibrating area. Putting $\tau_x = f\sigma\cos\beta$, $\tau_y = f\sigma\sin\beta$, $\sigma_x = \sigma\sin\beta$, $\sigma_y = \sigma\cos\beta$, where β – the angle of tangent inclination to the roll profile at B, we get

$$\frac{(x+k)(1-ftg\beta)}{tg\beta+f} = a-y. \tag{2}$$

Because tg$\beta = dy/dx$, then from (2) we will have the following differential equation:

$$[(a-y)+(x+k)f]dy + [(a-y)f-(x+k)]dx = 0. \tag{3}$$

The solution of this equation gives the form of rolls rational profile. After changing variables $\bar{y} = a - y$ and $\bar{x} = x + k$ we get:

$$(\bar{y}f - \bar{x})d\bar{x} - (\bar{y} + \bar{x}f)d\bar{y} = 0. \tag{4}$$

Let’s introduce a new variable $u = \bar{x}/\bar{y}$, then equation (4) takes the form

$$\left(\frac{f}{u} - 1\right)(ud\bar{y} + \bar{y}du) - \left(\frac{1}{u} + f\right)d\bar{y} = 0. \tag{5}$$

Convert (5) by separating the variables:

$$\frac{d\bar{y}}{\bar{y}} = \frac{(f-u)du}{(u^2+1)}. \tag{6}$$

After integration and inverse change of variables we have

$$f\mathrm{arctg}\frac{x+k}{a-y} = \ln C(a-y)\left[\left(\frac{x+k}{a-y}\right)^2 + 1\right]^{\frac{1}{2}}. \tag{7}$$

Let’s define the integration constant C from the condition $x = 0, y = 0$

$$C = \left[\exp(f\mathrm{arctg}\frac{k}{a})\right](k^2 + a^2)^{-\frac{1}{2}}.$$

After substitution value C in (7):

$$\exp\left[f\left(\mathrm{arctg}\frac{x+k}{a-y} - \mathrm{arctg}\frac{k}{a}\right)\right] = \sqrt{[(x+k)^2 + (a-y)^2]/(k^2+a^2)}. \tag{8}$$

We turn to the polar coordinates with a pole at point A, denoting

$$\mathrm{arctg}\frac{x+k}{a-y} = \beta_x, \qquad \mathrm{arctg}\frac{k}{a} = \beta_k,$$

$$(k^2 + a^2)^{1/2} = R_k, [(x+k)^2 + (a-y)^2]^{1/2} = R_x, \tag{9}$$

where

$$R_x = R_k \exp[f(\beta_x - \beta_k)]. \tag{10}$$

Here $\boldsymbol{R}_x$, β_x, $\boldsymbol{R}_k$, β_k – radius-vector and polar angle, respectively, for an arbitrary point of the roll profile and a point of interface between the profile and the calibrating section.

Equation (10) determines the rational profile of the roll in terms of rolls and supporting rings bearing surfaces uniform deterioration, as well as the balance of the rolls under one-sided load during rolling. The roll whose profile is configured on the curve calculated by this formula is shown in figure 2.

Figure 2. Roll with a curved profile.

4. Parametric analysis of the deformation conditions effect on the rolls geometry

Let us determine the length of the calibrating section from smooth conjugation condition of this section with the roll profile. At the mating point $\mathrm{tg}\beta = \frac{dy}{dx} = 0$. Then from equation (3) with $x = 0, y = 0$, $k = af$. If $f = 0$, then $k = 0$. So $\beta_n = 0$, $R_n = a$. From equation (10) we obtain $R_x = a$, i.e. with $f = 0$ roll profile is limited to a circle with a radius a.

When determining the roll profile, we need to know the value β_x for point C – where metal starts contact with the roll surface. Marking this angle β_C, from equation (8) with (9), assuming $\beta_x = \beta_C$, $y = \Delta d/2$, after transformation we will have

$$\exp[f(\beta_C - \beta_k)] = \frac{\cos\beta_k}{\cos\beta_C}\left(\frac{a-0{,}5\Delta d}{a}\right), \tag{11}$$

where Δd – diameter reduction.

Taking the logarithm of (11) and spread out in a row such type expression as $\ln\cos\beta$ with the first term retention of the expansion, we get

$$\beta_C{}^2 - 2f\beta_C + 2f\beta_k - \beta_k{}^2 + 2\ln\frac{a-0{,}5\Delta d}{a} = 0. \tag{12}$$

The solution of this equation gives

$$\beta_C = f + \left[(\beta_k - f)^2 - 2\ln\frac{a-0{,}5\Delta d}{a}\right]^{1/2}. \tag{13}$$

To use the obtained expressions to calculate the geometry of the roll, it is necessary to determine the value a, which depends on the supporting ring profile inclination angle α. Denote by β_n polar angle of a point n touching the roll profile with the ring generator in the polar coordinate system with the pole at the point A' (see fig. 1). From equation (3), assuming $\frac{dy}{dx} = \mathrm{tg}\alpha$, $(x_n + k)/(a - y_n) = \mathrm{tg}\beta_n$, where x_n, y_n – point n coordinates in system $X'0'Y'$, obtain

$$\mathrm{tg}\beta_n = (f + \mathrm{tg}\alpha)/(1 - f\mathrm{tg}\alpha). \tag{14}$$

Taking in (10) $R_x = R_n = (D - 2y_n)/\cos\beta_n$, $R_k = (D - y_n)/\cos\beta_k$, and $\beta_x = \beta_n$, will have

$$\frac{D-2y_n}{D-y_n}=\frac{\cos\beta_n}{\cos\beta_k}\exp[f(\beta_n-\beta_k)], \tag{15}$$

where D – roll barrel diameter.

Denoting the right side of the expression (15) through G, $y_n = D\,(G-1)/(G-2)$ can be written, where

$$a = D/(2-G). \tag{16}$$

When profiling a roll, it is necessary to know the position of the centers of curvature, i.e. profile evolute. The coordinates of curve curvature centers represented by equation (10) in the polar coordinate system

$$x_z = R_x\cos\bar{\beta}_x - \frac{(R_x^2+R_x'^2)(R_x\cos\bar{\beta}_x+R_x'\sin\bar{\beta}_x)}{R_x^2+2R_x'^2-R_xR_x''}; \tag{17}$$

$$y_z = R_x\sin\bar{\beta}_x - \frac{(R_x^2+R_x'^2)(R_x\sin\bar{\beta}_x-R_x'\cos\bar{\beta}_x)}{R_x^2+2R_x'^2-R_xR_x''},$$

where $\bar{\beta}_x = \beta_x - \beta_k$.

Because $R_x = R_k\exp(f\bar{\beta}_x)$, $R_x' = fR_k\exp(f\bar{\beta}_x)$, $R_x'' = f^2R_k\exp(f\bar{\beta}_x)$, obtain $x_z = -fR_k(\exp f\bar{\beta}_x)\sin\bar{\beta}_x$; $y_z = fR_k(\exp f\bar{\beta}_x)\cos\bar{\beta}_x$ or $x_z^2+y_z^2 = R_{xz}^2$, where $R_{xz} = fR_k\exp(f\bar{\beta}_x)$, so

$$R_{xz} = R_xf. \tag{18}$$

Thus, the radius vector of the roll profile evolution in the polar coordinate system with a pole at the point A is defined as the multiplication of the corresponding roll profile points radius-vector with the friction coefficient. With $f = 0$, $\boldsymbol{R}_{xz} = 0$. The center of curvature in this case is the point A.

The roll profile represented by expression (10) has a complex shape. To simplify the shape of the roll profile, we introduce the assumption that the resulting load acting on the profile section from the calibration section to the point B, is attached to the center of this site. Center coordinate $x_1 = x/2$, $y_1 = y/2$, where x and y – point B coordinates. For point with coordinates x_1, y_1, $\beta_1 = \beta/2$. Then

$$\mathrm{tg}\beta_1 = x/(2R-y), \tag{19}$$

where R – the ordinate of the intersection point with the axis y perpendicular to the tangent at the point of the profile with the coordinates x_1 and y_1. From equation (2) taking into account the values x_1, y_1, $k = af$, and (19), obtain

$$x^2+y^2+2\frac{a+fk-R}{f}x-2Ry = 0. \tag{20}$$

The expression (20) defines the coordinates of the roll profile, which generator is the envelope of circles family with the center coordinates $x_c = (R-fk-a)/f$, $y_c = R$.

Let's take $x_c = (R-fk-a)/f = 0$. Then $R = a+fk$. From equation (20) it follows that the roll profile is bounded by a circle with the center coordinates $x_c = 0$, $y_c = a+fk$. The calculation of the roll profile, bounded by a circle, with the formula (10) gives almost the same results, which allows to make a conclusion about the validity of the assumptions made.

Let us now consider the conditions under which the roll profile can be limited to a straight line. Applying the contact force resultant in the center of the blank reduction area with the center coordinates $x = \Delta d/4\mathrm{tg}\beta$, $y = \Delta d/4$, where β – the roll forming profile inclination angle, from the expression (2) we obtain

$$\mathrm{tg}\beta = \frac{\sqrt{16q^2-4\Delta d(\Delta d-4p)}}{2(\Delta d-4p)} \tag{21}$$

where $p = a + fk$, $q = k - fa$. With $k = fa$ parameter $q = 0$. So

$$\text{tg}\beta = \sqrt{\frac{\Delta d}{4(a+fk)-\Delta d}}. \quad (22)$$

Thus, the equilibrium position of the roll with a straight profile at a given β provided only for certain Δd. For a roll whose profile is limited by a circle, the parameter a is defined by the following expression

$$a = D/[n(1-\cos\alpha)+1], \quad (23)$$

where $n = 1 + f^2$.

In the considered design of the roll, the working and supporting parts are combined. Roller with a curved profile is in contact with the supporting surface of the ring at a point. A more rational is the contact in a straight line. To do this, it is advisable to use the design of the roll, in which the supporting and working parts are separated [17]. Then for a roll with a represented by expression (10) generator

$$a = (D - 0{,}5L\text{tg}\alpha)/(2-G). \quad (24)$$

Here L – the length of roll the support surface. For a roll with a profile made by equation (20), we get

$$a = (D - 0{,}5L\text{tg}\alpha)/[n(1-\cos\alpha)+1]. \quad (25)$$

5. Conclusion

Analytical dependences are obtained for calculating the rolls rational calibration during the round-rolled surface transverse rolling. The calibration use ensures uniform deterioration of the rolls and supporting rings bearing surfaces, as well as the rolls balance under one-sided load during rolling. The obtained results were used in rolls profiling for rolling the surface under laboratory and production conditions [19, 20].

References

[1] Suslov A G 2001 *Inzheneriia Poverkhnosti Detalei - Rezerv V Povyshenii Konkurentosposobnosti Mashin – Inzheneriia Poverkhnosti. Prilozhenie K Zhurnalu "Spravochnik. Inzhenernyi Zhurnal"* [*Part Surface Engineering - A Reserve in Improving The Competitiveness of Machines*] vol 4 (Moscow: Mashinostroenie) pp 3-9

[2] Shcherbinskii V G 2003 *Tekhnologiia Ul'trazvukovogo Kontrolia Svarnykh Soedinenii* [*Technology of Ultrasonic Testing of Welded Joints*] (Moscow: Tisso) pp 3-9

[3] GOST 24507-80 *Non-Destructive Testing. Forgings From Ferrous and Non-Ferrous Metals. Ultrasonic Methods of Slow Defection*

[4] Tselikov A I and Polukhin P I 1988 *Mashiny i Agregaty Metallurgicheskikh Zavodov. Tom 3. Mashiny i Agregaty Dlia Proizvodstva i Otdelki Prokata* [*Machines and Units Of Metallurgical Plants. Machines and Units for The Production and Finishing of Steel*] Vol 3 (Moscow: Metallurgiia) p 576

[5] GOST 2789-73 *Surface Roughness. Parameters and Characteristics*

[6] Egorov M E, Dement'ev V I and Dmitriev V L 1976 *Tekhnologiia Mashinostroeniia* [*Engineering Technology*] (Moscow: Vysshaia shkola) p 535

[7] GOST 14955-77 *Quality Round Steel With Special Surface Finishing. Specifications*

[8] Bernshtein M L 1979 *Atlas Defektov Stali* [*Atlas of Steel Defects*] (Moscow: Metallurgiia) p 185

[9] GOST 18296-72 *Surface Working. Terms And Definitions*

[10] Zaides S A 2007 *Tekhnologicheskie Protsessy Poverkhnostnogo Plasticheskogo Deformirovaniia: Monografiia* [*Technological Processes of Surface Plastic Deformation: Monograph*] (Irkutsk: Irkutsk State Technical University Press) p 404

[11] Odintsov L G 1968 *Uprochnenie i Otdelka Detalei Poverkhnostnym Deformirovaniem: Spravochnik* [*Hardening and Finishing of Parts by Surface Deformation: Handbook*] (Moscow: Mashinostroenie) p 328

[12] Papshev D D 1968 *Uprochnenie Detalei Obkatkoi Sharikami* [*Hardening Parts Run-In Balls*],

(Moscow: Mashinostroenie) p 132
[13] Braslavskii V M 1976 *Tekhnologiia Obkatki Krupnykh Detalei Rolikami* [*Technology Running Large Parts Rollers*] (Moscow: Mashinostroenie) p 158
[14] Smelianskii V M 2002 *Mekhanika Uprochneniia Detalei Poverkhnostnym Plasticheskim Deformirovaniem* [*Mechanics of Hardening of Parts by Surface Plastic Deformation*] (Moscow: Mashinostroenie) p 300
[15] Oleinik N V, Kychin V P and Lugovskoi A L 1984 *Poverkhnostnoe Dinamicheskoe Uprochnenie Detalei Mashin* [*Surface Dynamic Hardening of Machine Parts*] (Kiev: Tekhnika) p 151
[16] Bisk M B, Grekhov I A and Slavin V B 1973 *Kholodnaia Deformatsiia Stal'nykh Trub* [*Cold Deformation of Steel Pipe*s] part 2 (Sverdlovsk: Sredne-Ural'sk press) p 231
[17] Smirnov V V 1973 USSR Patent 398313
[18] Kalabushev V N, Medvedev B P and Davydov V I 1979 USSR Patent 685389
[19] Antimonov A M and Pushkareva N B 2019 *J. Materials Science Forum* 946 **3** 744-749
[20] Antimonov A M and Pushkareva N B 2018 Surface Pressure Treatment of Titanium Alloy Bars by Transverse Rolling *J. of Industrial Engineering* JOIE04(2018)6